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Carralero et al.

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(54) **MULTIFUNCTIONAL OPTICAL SENSOR UNIT**

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G02B 6/10	(2006.01)
G01D 5/26	(2006.01)

(52) **U.S. Cl.**

CPC . ***G02B 6/10*** (2013.01); ***G01D 5/268*** (2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

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(57) **ABSTRACT**

A method and apparatus for detecting a group of parameters. An optical signal is sent into an optical sensor unit comprising a first reflective structure, a second reflective structure, and a cavity system located between the first reflective structure and the second reflective structure. The first reflective structure is configured to be associated with an optical fiber. A response generated by the optical sensor unit is detected. The group of parameters is identified from the response.

20 Claims, 13 Drawing Sheets

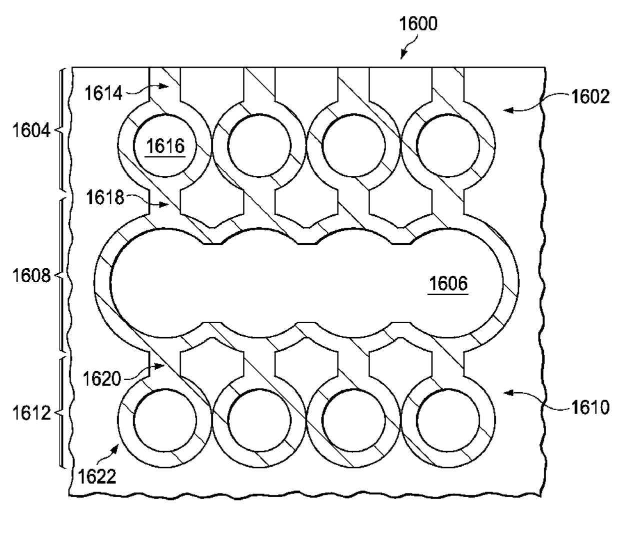

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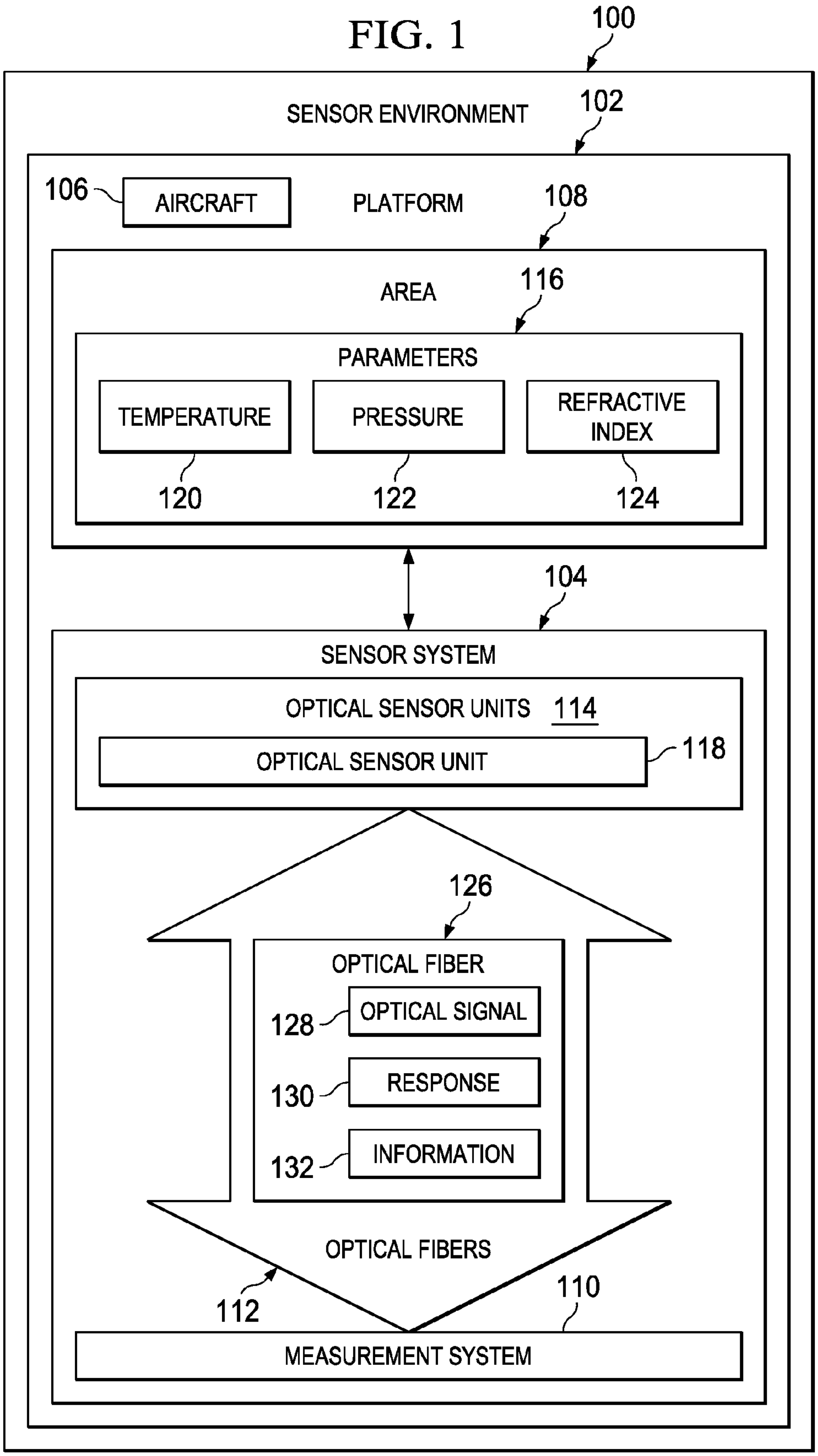
FIG. 1


100
SENSOR ENVIRONMENT
102
106
AIRCRAFT
PLATFORM
108
AREA
116
PARAMETERS
TEMPERATURE
PRESSURE
REFRACTIVE INDEX
120
122
124
104
SENSOR SYSTEM
OPTICAL SENSOR UNITS 114
OPTICAL SENSOR UNIT
118
126
OPTICAL FIBER
128
OPTICAL SIGNAL
130
RESPONSE
132
INFORMATION
OPTICAL FIBERS
112
110
MEASUREMENT SYSTEM

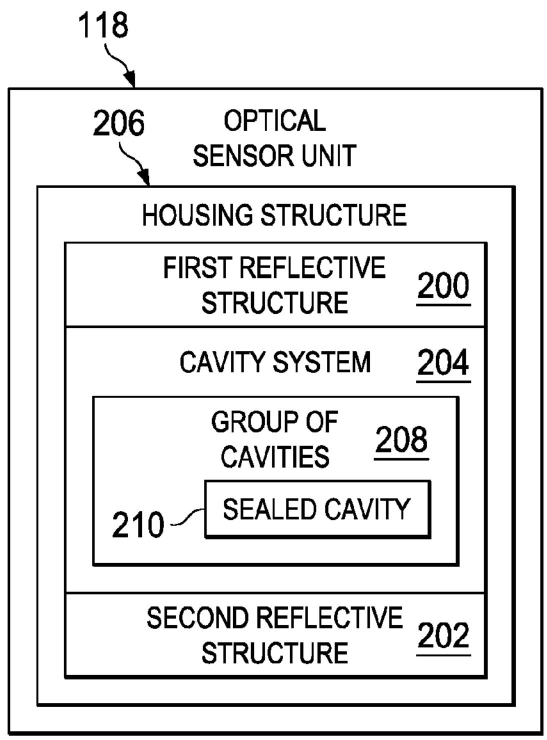

118
206
OPTICAL SENSOR UNIT
HOUSING STRUCTURE
FIRST REFLECTIVE STRUCTURE 200
CAVITY SYSTEM 204
GROUP OF CAVITIES 208
210
SEALED CAVITY
SECOND REFLECTIVE STRUCTURE 202

FIG. 2

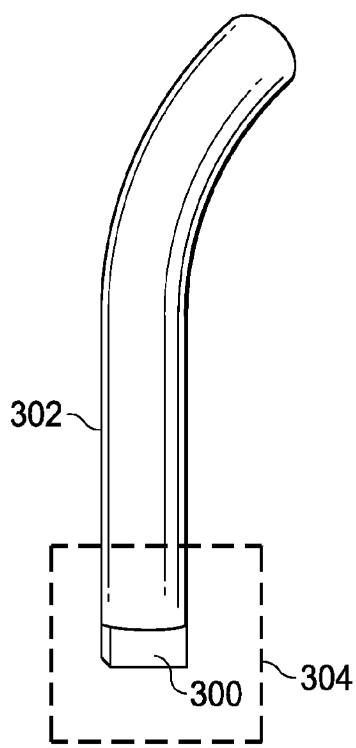

302
300
304

FIG. 3

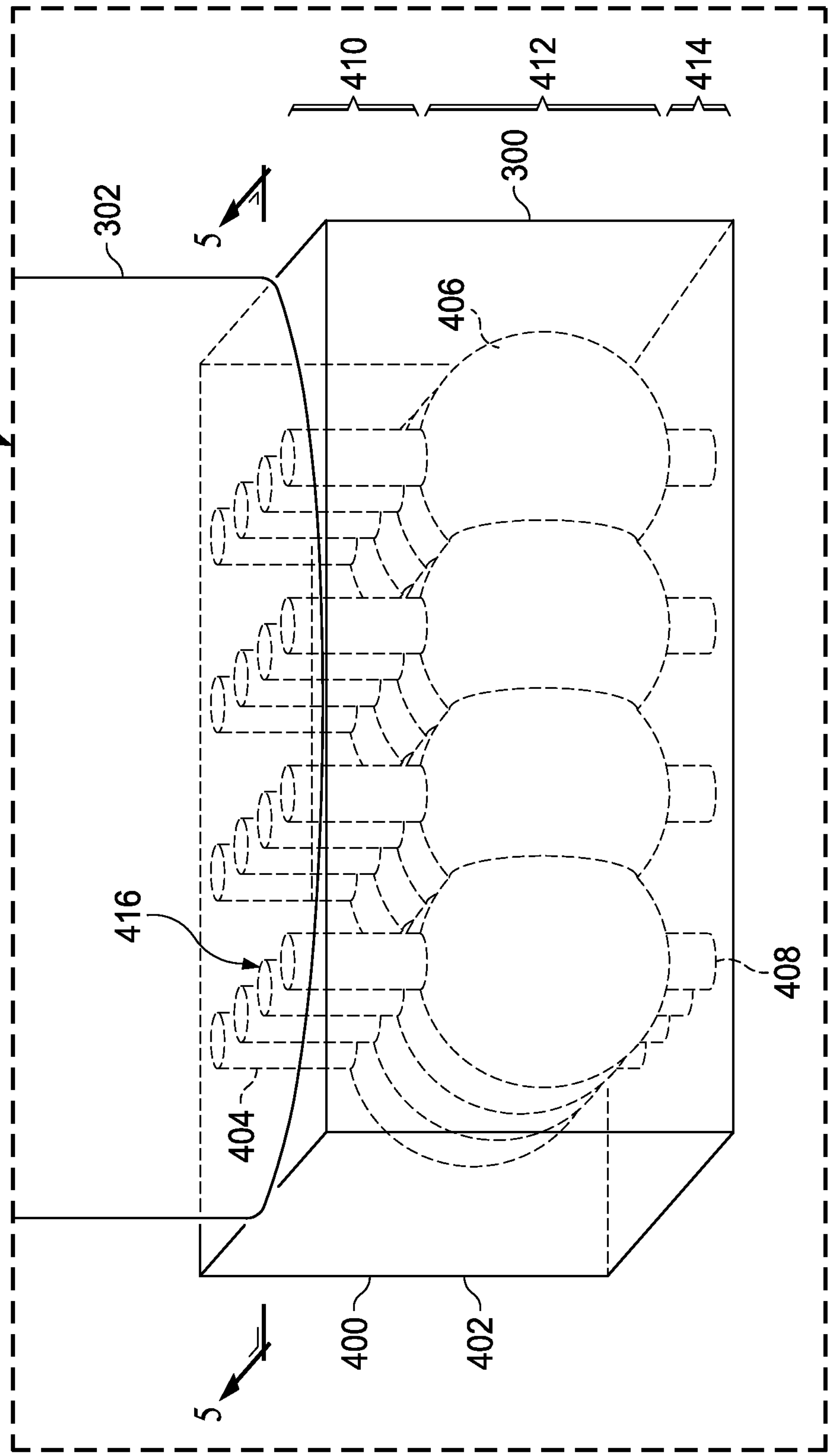


FIG. 4

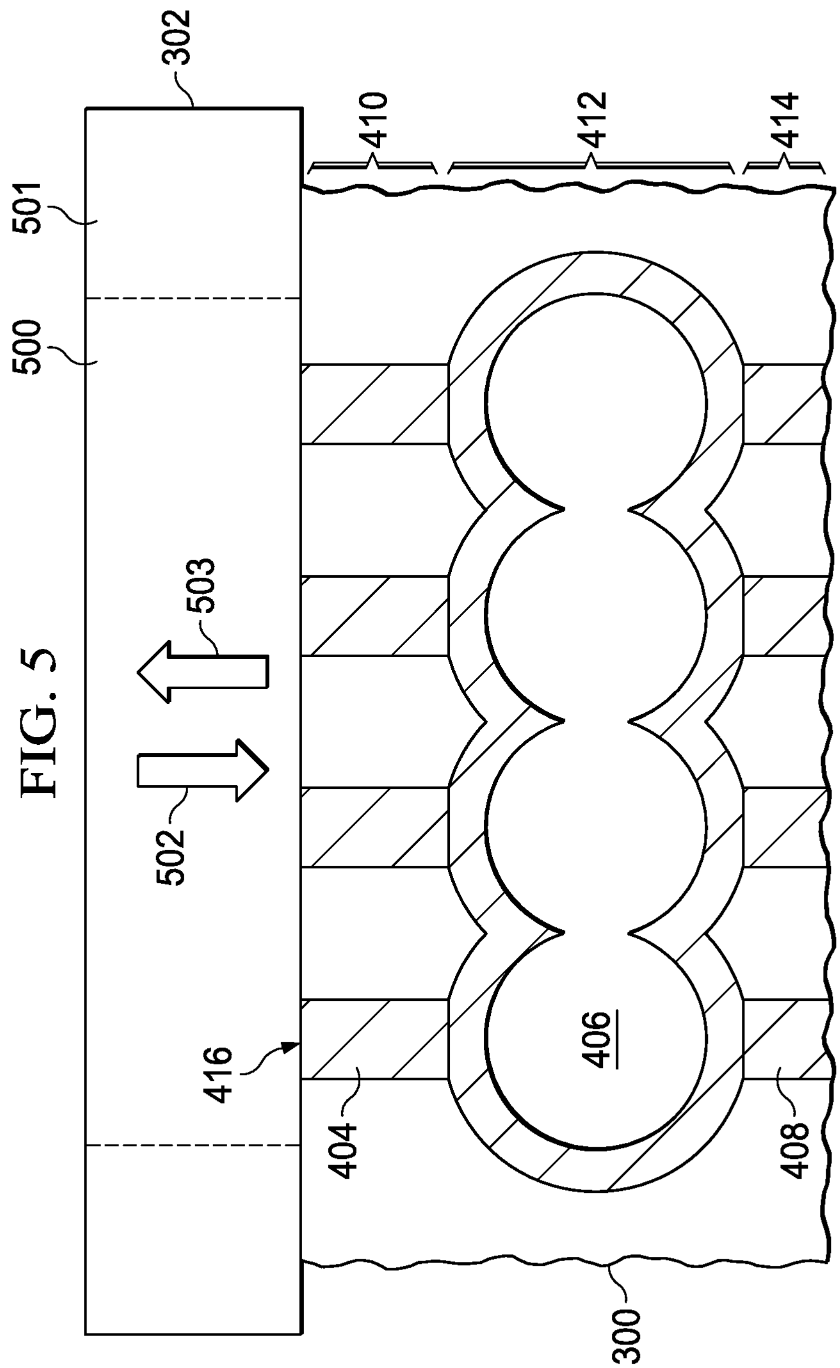


FIG. 5

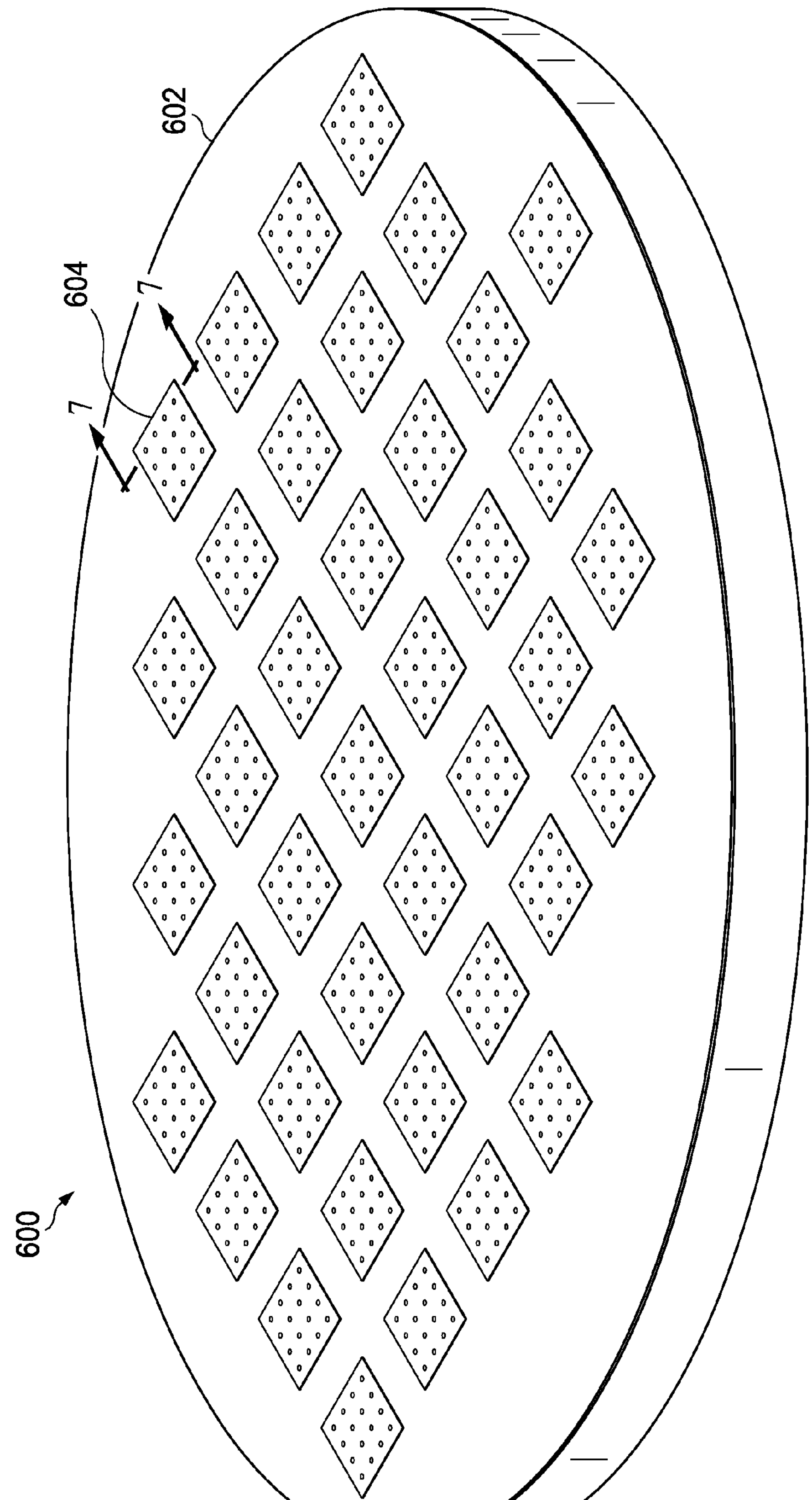


FIG. 6

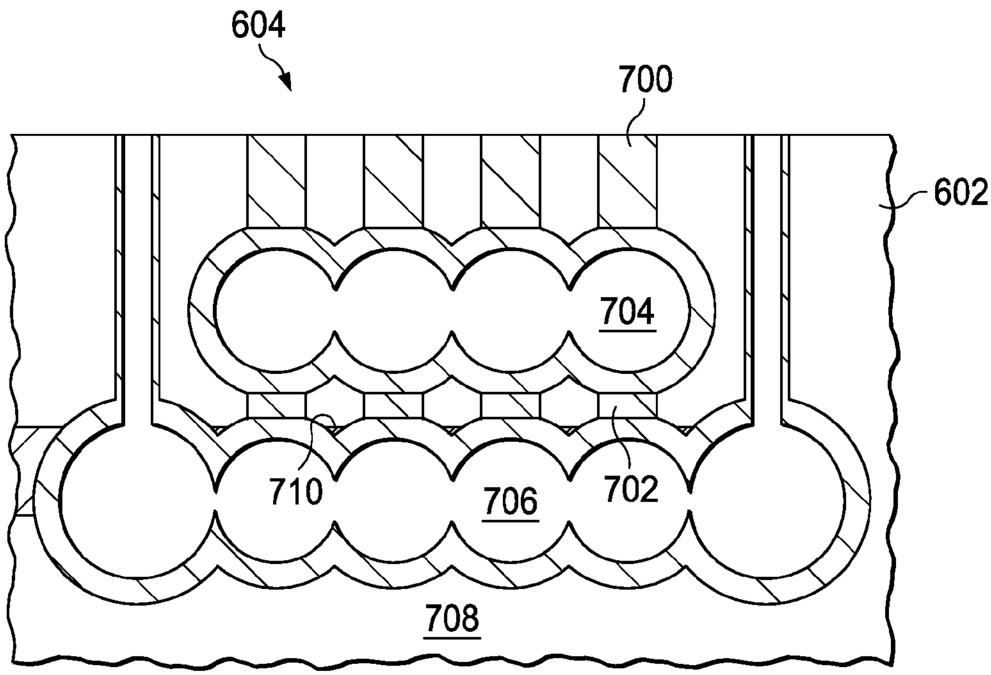


FIG. 7

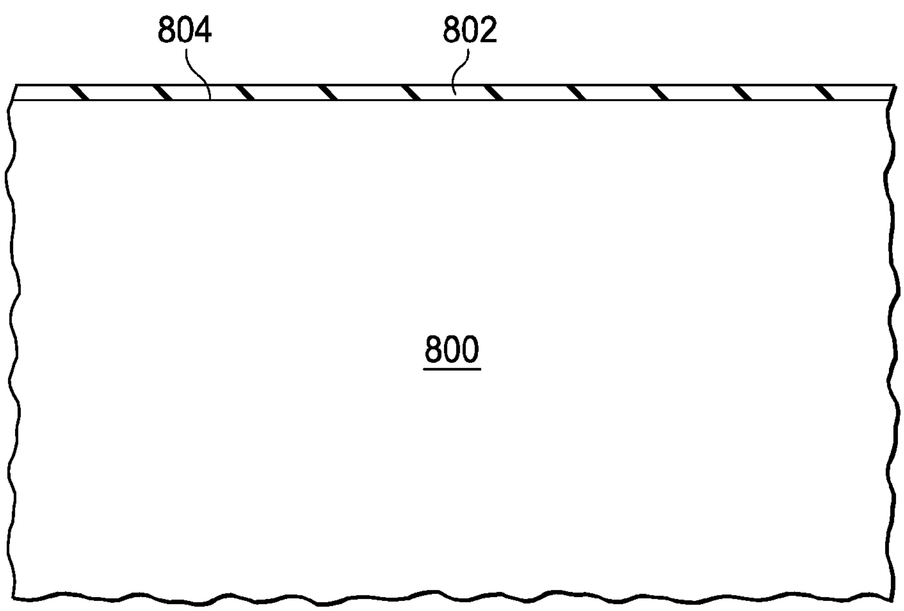


FIG. 8

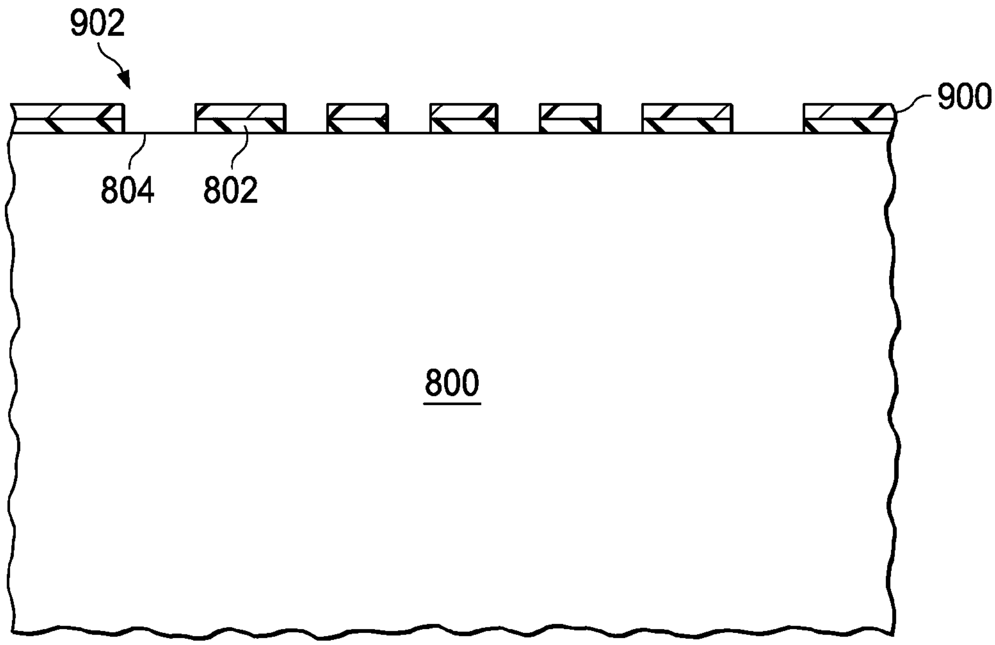


FIG. 9

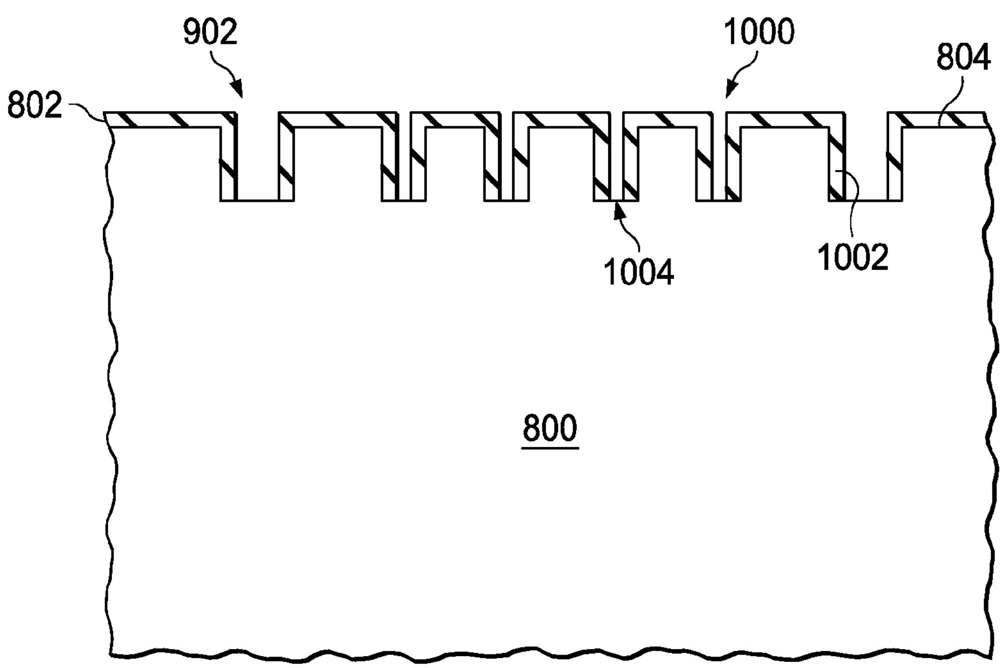


FIG. 10

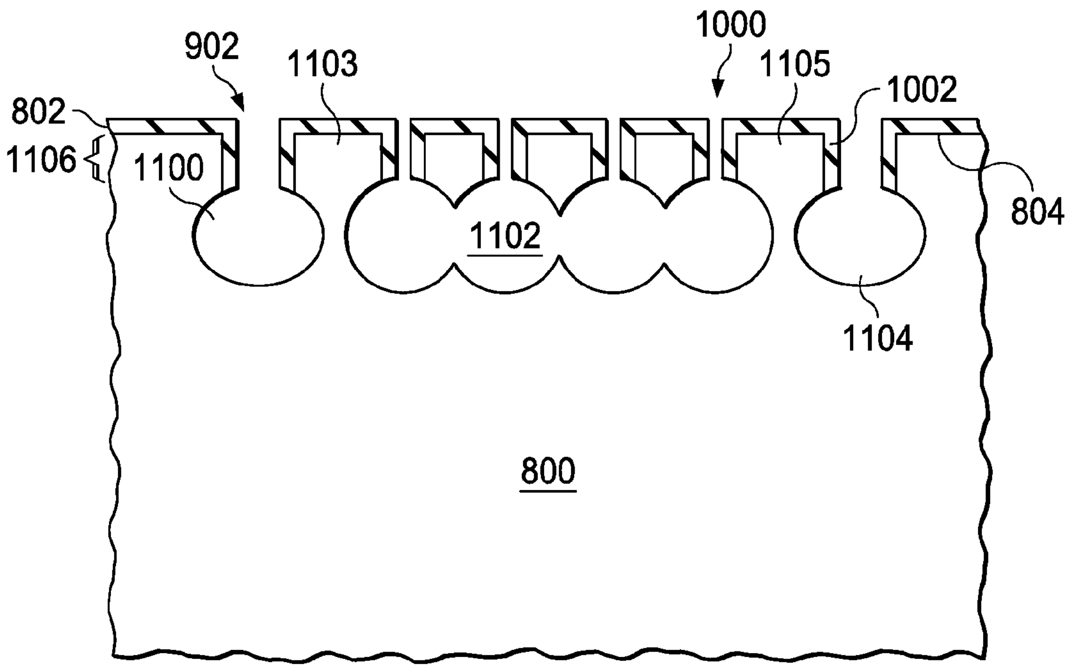

902
1103
1000
1105
1002
802
1106
1100
1102
804
1104
800

FIG. 11

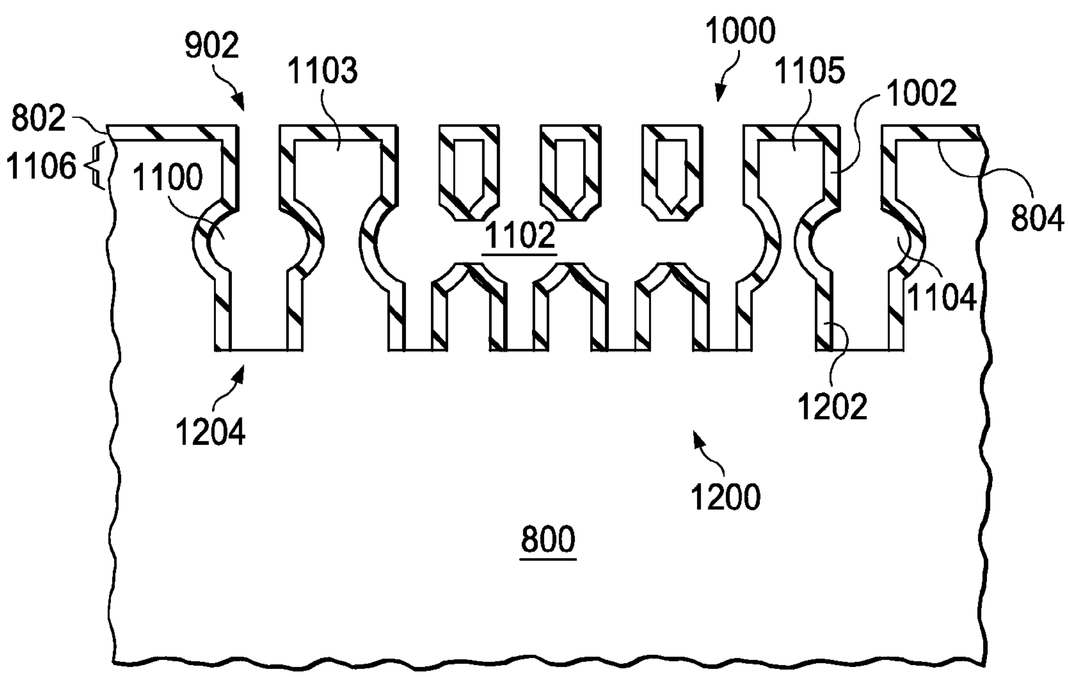

902
1103
1000
1105
1002
802
1106
1100
1102
804
1104
1204
1202
1200
800

FIG. 12

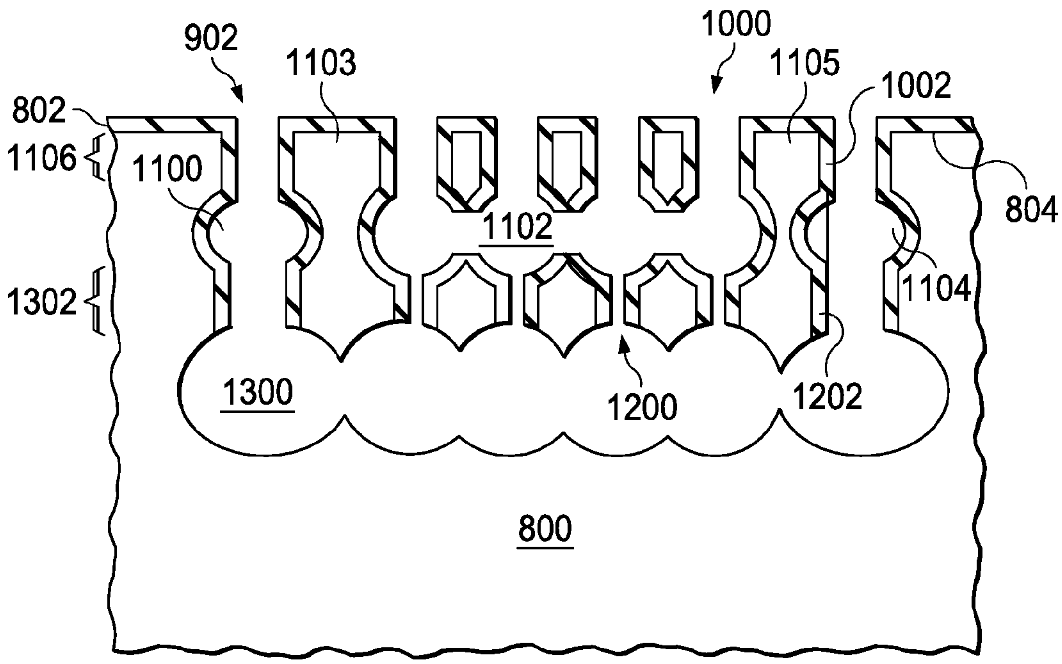

902
1103
1000
1105
1002
802
1106
1100
804
1102
1104
1302
1300
1200
1202
800

FIG. 13

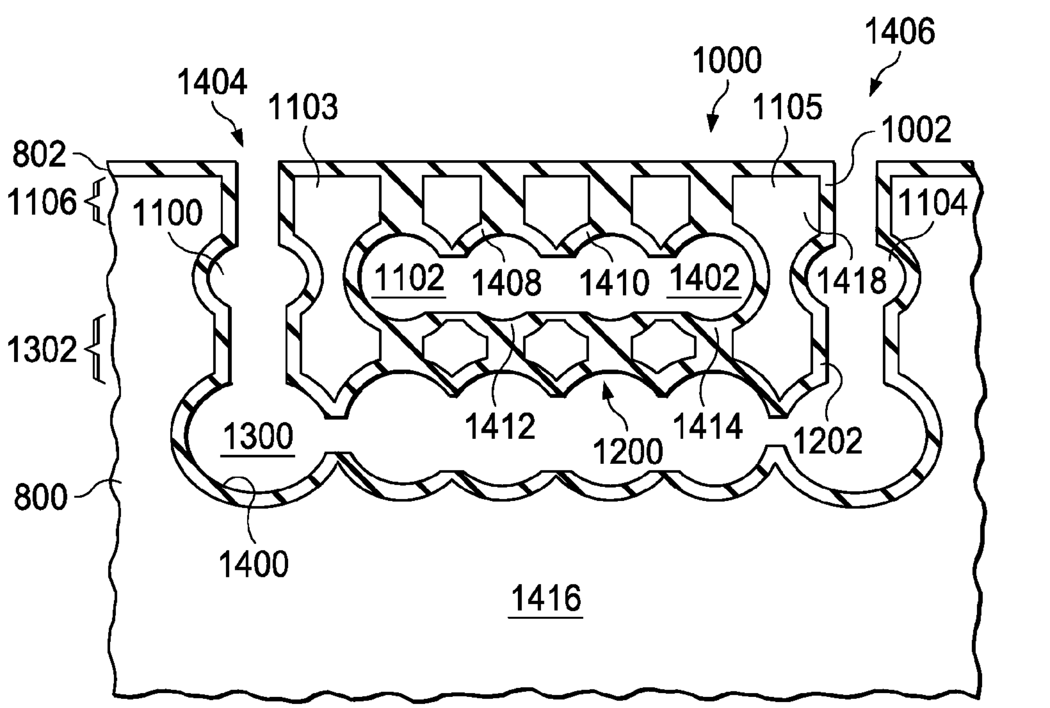

1406
1000
1404
1103
1105
1002
802
1106
1100
1104
1102
1408
1410
1402
1418
1302
1412
1414
1300
1200
1202
800
1400
1416

FIG. 14

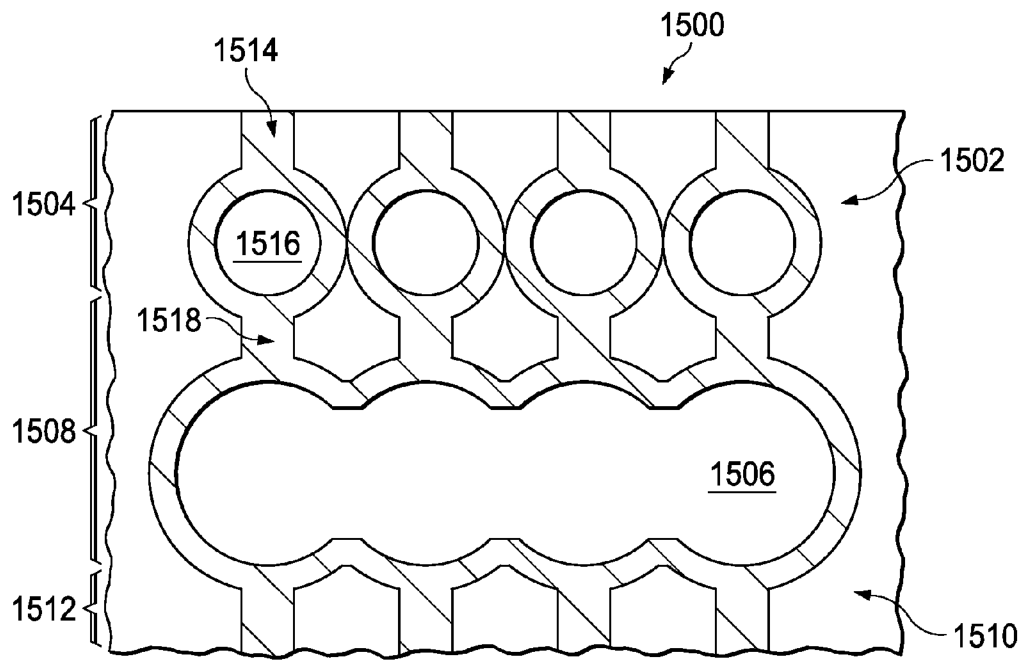

1500
1514
1502
1504
1516
1518
1508
1506
1512
1510

FIG. 15

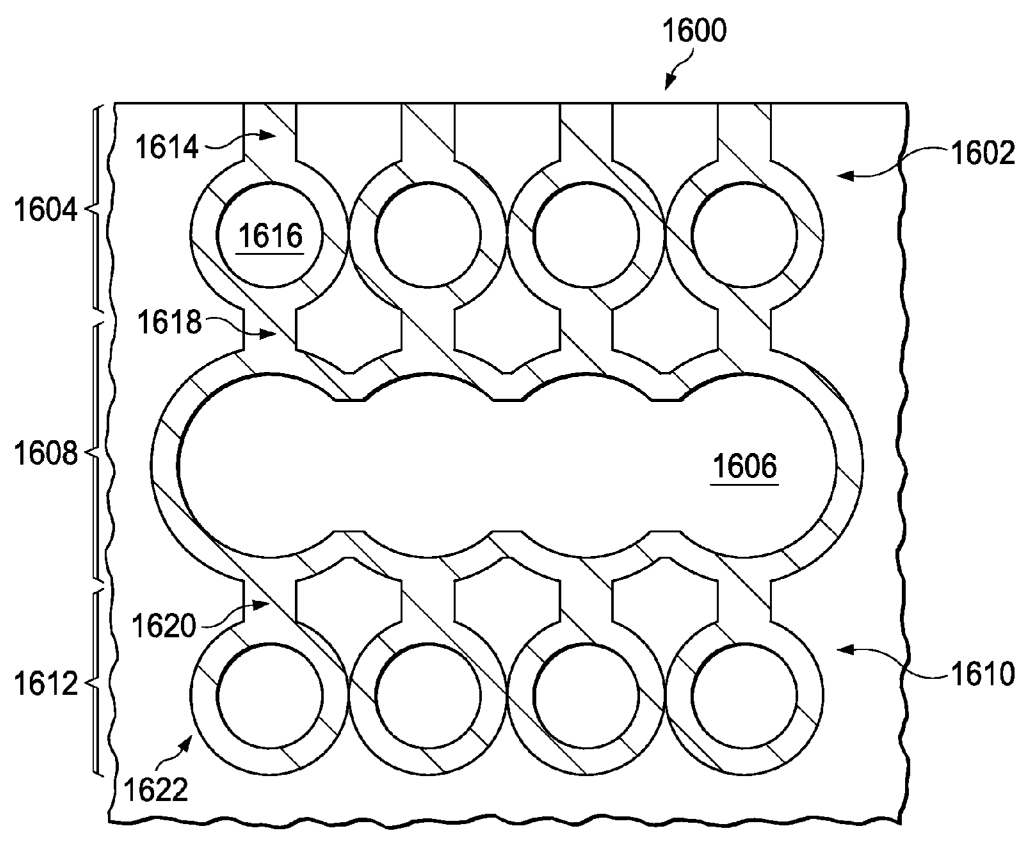

1600
1614
1602
1604
1616
1618
1608
1606
1620
1612
1610
1622

FIG. 16

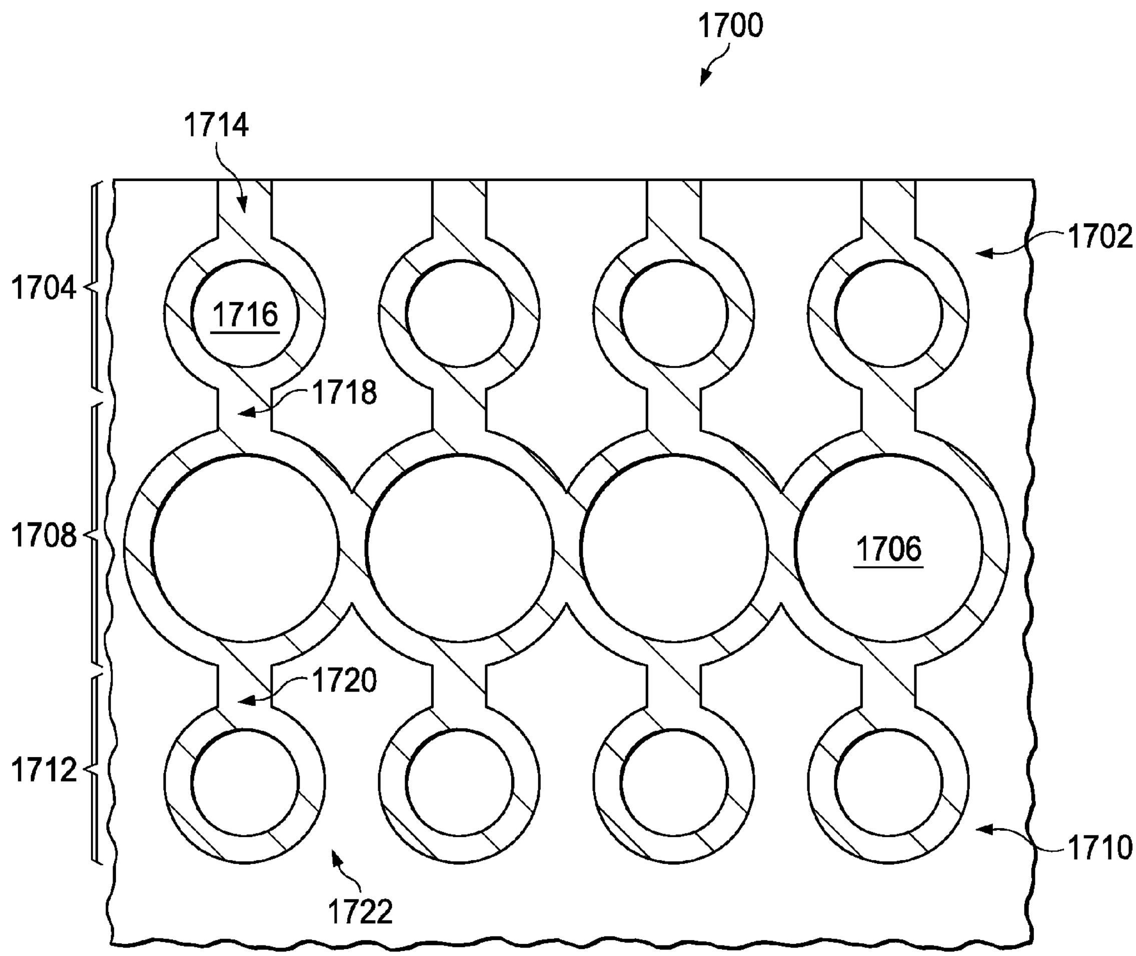


FIG. 17

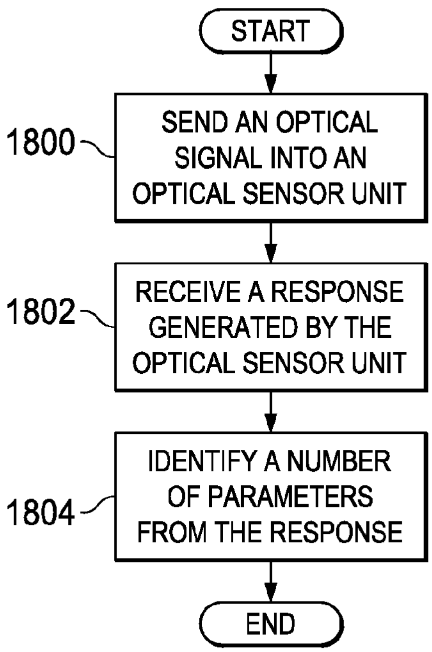

START
SEND AN OPTICAL SIGNAL INTO AN OPTICAL SENSOR UNIT
1800
RECEIVE A RESPONSE GENERATED BY THE OPTICAL SENSOR UNIT
1802
IDENTIFY A NUMBER OF PARAMETERS FROM THE RESPONSE
1804
END

FIG. 18

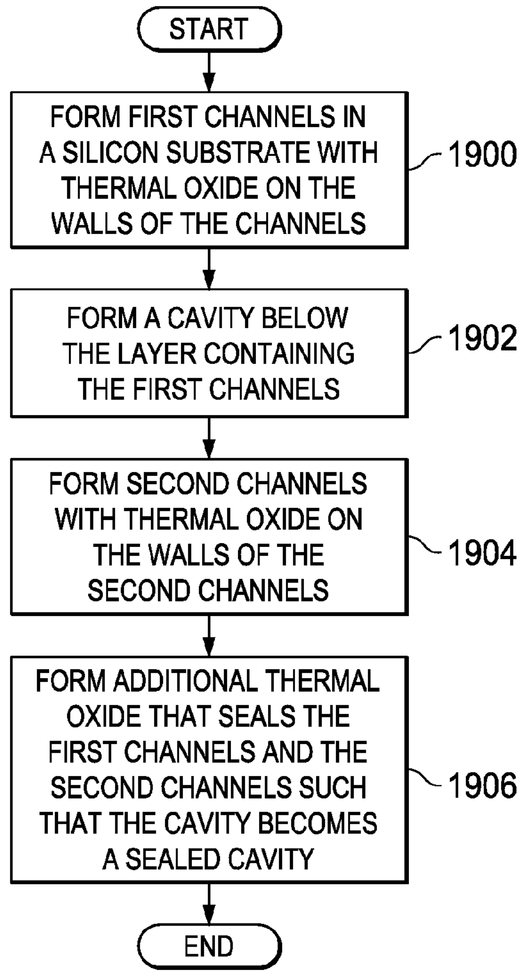

START
FORM FIRST CHANNELS IN A SILICON SUBSTRATE WITH THERMAL OXIDE ON THE WALLS OF THE CHANNELS
1900
FORM A CAVITY BELOW THE LAYER CONTAINING THE FIRST CHANNELS
1902
FORM SECOND CHANNELS WITH THERMAL OXIDE ON THE WALLS OF THE SECOND CHANNELS
1904
FORM ADDITIONAL THERMAL OXIDE THAT SEALS THE FIRST CHANNELS AND THE SECOND CHANNELS SUCH THAT THE CAVITY BECOMES A SEALED CAVITY
1906
END

FIG. 19

FIG. 20

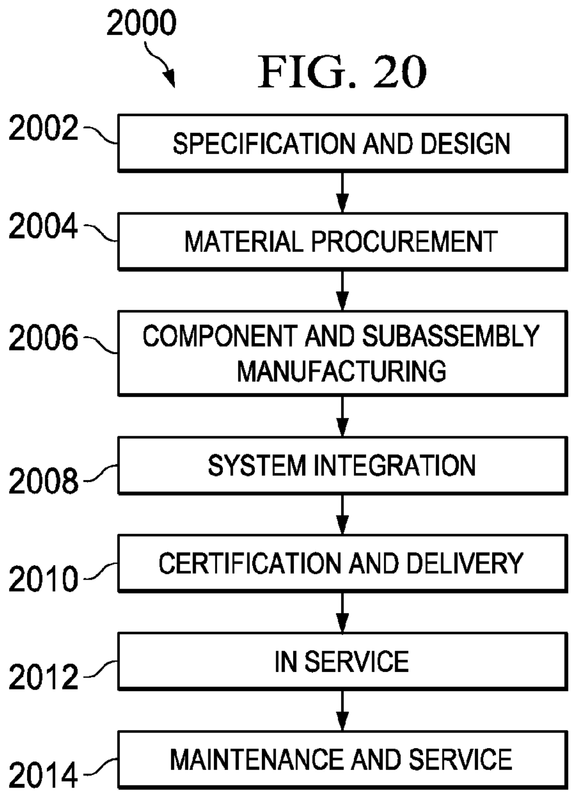
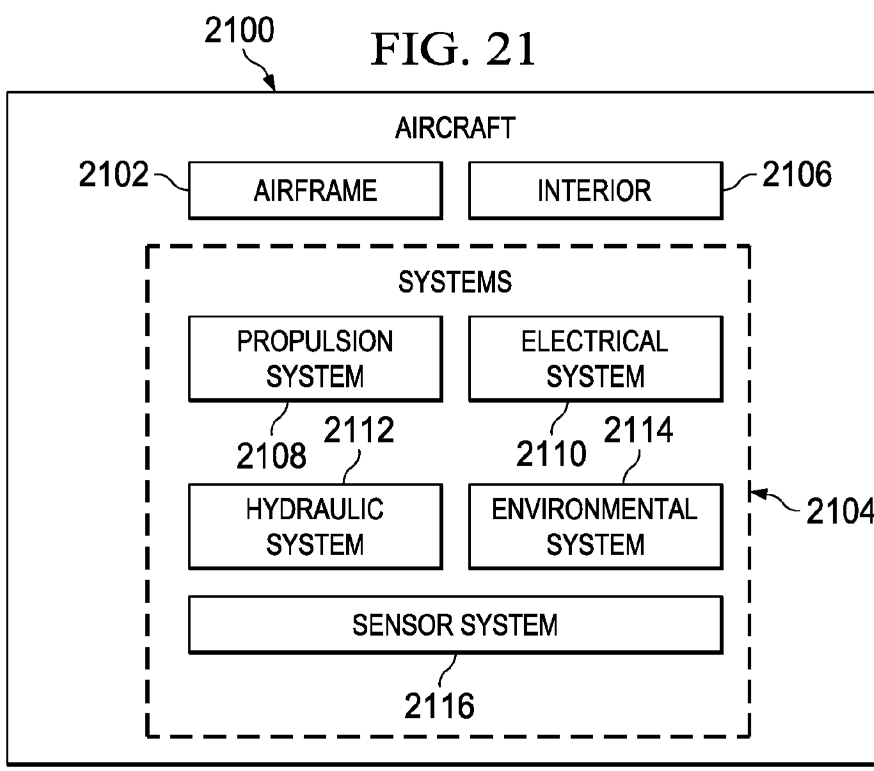

2000
2002
SPECIFICATION AND DESIGN
2004
MATERIAL PROCUREMENT
2006
COMPONENT AND SUBASSEMBLY MANUFACTURING
2008
SYSTEM INTEGRATION
2010
CERTIFICATION AND DELIVERY
2012
IN SERVICE
2014
MAINTENANCE AND SERVICE

FIG. 21


2100
AIRCRAFT
2102
AIRFRAME
INTERIOR
2106
SYSTEMS
PROPULSION SYSTEM
ELECTRICAL SYSTEM
2108
2112
2110
2114
HYDRAULIC SYSTEM
ENVIRONMENTAL SYSTEM
2104
SENSOR SYSTEM
2116

MULTIFUNCTIONAL OPTICAL SENSOR UNIT

BACKGROUND INFORMATION

1. Field

The present disclosure relates generally to sensors and, in particular, to optical sensors. Still more practically, the present disclosure relates to a method and apparatus for an optical sensor for detecting multiple types of parameters.

2. Background

Many different types of sensors may be used to detect a physical quantity and generate a signal with information about the physical quantity detected. The physical quantity may also be referred to as a parameter. For example, electrical sensors have been commonly used to detect parameters, such as temperature, pressure, and other types of physical quantities. For example, an electrical sensor may be used to detect temperature and pressure within an interior of the fuel tank of an aircraft.

When electrical sensors are used within a fuel tank, wires connecting the sensors to power and other devices in the aircraft extend into the fuel tank through openings formed in the fuel tank. These openings are sealed to prevent fuel from exiting the fuel tank. In detecting parameters such as fuel level, temperature, pressure, and other parameters, wires are used for each of the types of sensors located within the fuel tank.

With the use of electrical sensors, challenges with respect to shielding and grounding are present. Providing shielding for sensors such that the sensors may operate in a desired manner without causing an undesired condition in the fuel tank is desirable but challenging at times. These challenges increase with the use of composite materials. For example, when a fuel tank is formed from a composite material, shielding is more limited as compared to fuel tanks formed of metal materials. With a composite fuel tank, the inherent shielding and protection of a metal wall in a metal fuel tank is reduced or unavailable. As a result, additional systems are needed for a desired use and operation of an electrical sensor system.

Further, the size of electrical sensors may be larger than desired. For example, a capacitive sensor for detecting a level fuel in the fuel tank may be more complex than desired.

Issues with the use of electrical sensors may also be present for other locations in aircraft. As an example of an issue with respect to the use of electrical sensors in an engine of an aircraft, the heat generated by the engine of an aircraft may present challenges with respect to electrical sensors operating with a desired level of performance.

As a result, the space by the electrical sensors and associated devices, installation time, and other factors may be greater than desired. Therefore, it would be desirable to have a method and apparatus that takes into account at least some of the issues discussed above, as well as other possible issues.

SUMMARY

In one illustrative embodiment, an apparatus comprises a first reflective structure, a second reflective structure, and a cavity system located between the first reflective structure and the second reflective structure. The first reflective structure is configured to be associated with an optical fiber.

In another illustrative embodiment, an optical sensor unit comprises a first photonic crystal mirror, a second photonic crystal mirror, and a sealed cavity located between the first photonic crystal mirror and the second photonic crystal mirror.

In yet another illustrative embodiment, a method for detecting a group of parameters is provided. An optical signal is sent into an optical sensor unit comprising a first reflective structure, a second reflective structure, and a cavity system located between the first reflective structure and the second reflective structure. The first reflective structure is configured to be associated with an optical fiber. A response generated by the optical sensor unit is detected. The group of parameters is identified from the response.

The features and functions can be achieved independently in various embodiments of the present disclosure or may be combined in yet other embodiments in which further details can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the illustrative embodiments are set forth in the appended claims. The illustrative embodiments, however, as well as a preferred mode of use, further objectives and features thereof, will best be understood by reference to the following detailed description of an illustrative embodiment of the present disclosure when read in conjunction with the accompanying drawings, wherein:

FIG. **1** is an illustration of a block diagram of a sensor environment in accordance with an illustrative embodiment;

FIG. **2** is an illustration of a block diagram of a sensor unit in accordance with an illustrative embodiment;

FIG. **3** is an illustration of an optical sensor unit associated with optical fiber in accordance with an illustrative embodiment;

FIG. **4** is a more detailed illustration of a sensor unit associated with an optical fiber in accordance with an illustrative embodiment;

FIG. **5** is an illustration of a cross-sectional view of an optical sensor unit associated with an optical fiber in accordance with an illustrative embodiment;

FIG. **6** is an illustration of optical sensor units in a silicon substrate in accordance with an illustrative embodiment;

FIG. **7** is an illustration of a cross-sectional view of an optical sensor unit in a wafer in accordance with an illustrative embodiment;

FIGS. **8-14** are illustrations of cross-sectional views for a process for fabricating an optical sensor unit on a silicon substrate in accordance with an illustrative embodiment;

FIG. **15** is an illustration of a cross-sectional view of an optical sensor unit in accordance with an illustrative embodiment;

FIG. **16** is another illustration of a cross-sectional view of an optical sensor unit in accordance with an illustrative embodiment;

FIG. **17** is yet another illustration of a cross-sectional view of an optical sensor unit in accordance with an illustrative embodiment;

FIG. **18** is an illustration of a flowchart of a process for detecting a number of parameters in accordance with an illustrative embodiment;

FIG. **19** is an illustration of a flowchart of a process for forming an optical sensor unit in accordance with an illustrative embodiment;

FIG. **20** is an illustration of a block diagram of an aircraft manufacturing and service method in accordance with an illustrative embodiment; and

FIG. **21** is an illustration of a block diagram of an aircraft in which an illustrative embodiment may be implemented.

DETAILED DESCRIPTION

Illustrative embodiments recognize and take into account one or more of different considerations. Illustrative embodiments recognize and take into account that optical sensors may have advantages over electrical sensors. For example, optical sensors that use optical fibers are immune to electromagnetic interference. Additionally, optical sensors may increase the ease for remote sensing and may be smaller as compared to electrical sensors.

The illustrative embodiments also recognize and take into account that with optical sensors, optical fibers may extend through openings into a fuel tank. With optical fibers, issues associated with shielding and grounding are absent.

Illustrative embodiments also recognize and take into account that the number of optical fibers used may be reduced by designing optical sensors that detect multiple parameters. For example, one or more of the illustrative embodiments provide an optical sensor that comprises a sensor unit attached to an end of an optical fiber. The optical sensor unit is configured to detect multiple parameters in the illustrative embodiments.

In one illustrative embodiment, an apparatus comprises a first reflective structure, a second reflective structure, and a cavity system. The first reflective structure is configured to be associated with an optical fiber. The cavity system is located between the first reflective structure and the second reflective structure. These structures form an optical sensor unit in one illustrative example. The optical sensor unit is configured to detect multiple parameters. These parameters may include, for example, at least one of temperature, pressure, and a refractive index.

With reference now to the figures and in particular with reference to FIG. **1**, an illustration of a sensor environment is depicted in accordance with an illustrative embodiment. In this illustrative example, sensor environment **100** includes platform **102**. Sensor system **104** is associated with platform **102**.

As depicted, platform **102** may be aircraft **106**. Of course, platform **102** may take other forms other than aircraft **106**. For example, platform **102** may be, for example, a mobile platform, a stationary platform, a land-based structure, an aquatic-based structure, and a space-based structure. More specifically, the platform, may be a surface ship, a tank, a personnel carrier, a train, a spacecraft, a space station, a satellite, a submarine, an automobile, a power plant, a bridge, a dam, a house, a manufacturing facility, a building, or other suitable platforms.

As depicted, sensor system **104** is configured to monitor area **108** in platform **102**. Area **108** may take various forms. For example, when platform **102** takes the form of aircraft **106**, area **108** may be a fuel tank, an engine, or some other suitable area in aircraft **106**.

In this illustrative example, sensor system **104** includes a number of different components. As illustrated, sensor system **104** comprises measurement system **110**, optical fibers **112**, and optical sensor units **114**.

Optical fibers **112** connect optical sensor units **114** to measurement system **110**. Optical fibers **112** may be selected from at least one of multimode optical fibers and single mode optical fibers.

As used herein, the phrase "at least one of", when used with a list of items, means different combinations of one or more of the listed items may be used and only one of each item in the list may be needed. For example, "at least one of item A, item B, and item C" may include, without limitation, item A or item A and item B. This example also may include item A, item B, and item C or item B and item C. In other examples, "at least one of" may be, for example, without limitation, two of item A, one of item B, and ten of item C; four of item B and seven of item C; and other suitable combinations.

A multimode optical fiber is configured to carry light having more than one mode. A single mode optical fiber is configured to only carry light in a single mode. In these illustrative examples, the mode is a specific manner of propagation for light. For example, the mode may be defined by a spatial shape for the light.

In these illustrative examples, optical sensor units **114** are configured to detect group of parameters **116** in area **108**. As used herein, "a group of", when used with reference to items, means one or more items. For example, group of parameters **116** is one or more parameters.

In this illustrative example, optical sensor unit **118** in optical sensor units **114** may be comprised of one or more sensors in which each sensor may detect one or more parameters in group of parameters **116**. In detecting group of parameters **116**, values for those parameters are identified in the different illustrative examples. As depicted, optical sensor unit **118** is configured to detect at least one of temperature **120**, pressure **122**, and refractive index **124**. In other words, optical sensor unit **118** may be used to detect values for at least one of temperature **120**, pressure **122**, and refractive index **124**. As depicted, other optical sensors in group of optical sensor units **114** may detect the same or other parameters in group of parameters **116**. Group of optical sensor units **114** may also be used to detect other parameters. These parameters may include, for example, without limitation, at least one of vibration, acceleration, magnetic force, and other suitable parameters. In this manner, optical sensor unit **118** may function as a multifunctional optical sensor unit.

Optical sensor unit **118** is connected to measurement system **110** by optical fiber **126**. As depicted, optical sensor unit **118** is configured to receive optical signal **128** from measurement system **110** over optical fiber **126**. Optical signal **128** is light. In this illustrative example, optical signal **128** may have various characteristics that may be selected by measurement system **110**. For example, optical signal **128** may have at least one of a particular frequency, intensity, and duration.

In response to receiving optical signal **128**, optical sensor unit **118** is configured to generate response **130**. Response **130** is light generated from optical signal **128**. As depicted, response **130** travels back to measurement system **110** over optical fiber **126**. Measurement system **110** is configured to detect response **130**. In this illustrative example, response **130** contains information **132**. Information **132** is used to identify group of parameters **116**.

With reference now to FIG. **2**, an illustration of a block diagram of a sensor unit is depicted in accordance with an illustrative embodiment. In this example, a number of components are illustrated for optical sensor unit **118**. As depicted, optical sensor unit **118** comprises first reflective structure **200**, second reflective structure **202**, and cavity system **204**. These different structures are associated with housing structure **206** in this illustrative example. In particular, these different structures may be located on or within housing structure **206**.

When one component is "associated" with another component, the association is a physical association in the depicted examples. For example, a first component may be considered to be associated with a second component by being secured to the second component, bonded to the second component, mounted to the second component, welded to the second component, fastened to the second component, and/or connected to the second component in some other suitable manner. The first component also may be connected to the second component using a third component. The first component may also be considered to be associated with the second component by being formed as part of and/or an extension of the second component.

First reflective structure **200** is configured to be associated with optical fiber **126**. In particular, first reflective structure **200** may be associated with the end of optical fiber **126**. In this illustrative example, first reflective structure **200** may be, for example, bonded to optical fiber **126**, formed as part of optical fiber **126**, or connected directly or indirectly in some other manner to optical fiber **126**.

In one illustrative example, first reflective structure **200** may be bonded to optical fiber **126** using adhesives or epoxies. In another illustrative example, first reflective structure **200** may be fusion bonded to the optical fiber **126**. Further, first reflective structure **200** may also be physically or chemically bonded to optical fiber **126** in yet other illustrative examples.

In this illustrative example, cavity system **204** is located between first reflective structure **200** and second reflective structure **202**. For example, first reflective structure **200** may be located on a first side of cavity system **204**, while second reflective structure **202** may be located on a second side of cavity system **204** with the first side and second side being opposite of each other. As depicted, cavity system **204** may be comprised of a group of cavities **208**.

In these illustrative examples, group of cavities **208** includes sealed cavity **210**. Sealed cavity **210** may be sealed against the entry or exit of fluids from sealed cavity **210**. Sealed cavity **210** does not prohibit the transmission of optical signal **128** into sealed cavity **210**, out of sealed cavity **210**, within sealed cavity **210**, or some combination thereof.

First reflective structure **200** and second reflective structure **202** may be comprised of a number of different types of materials. For example, first reflective structure **200** and second reflective structure **202** may be each selected from one of a photonic crystal mirror, a layer of metal, a layer of dielectric, a grating, a Bragg grating, a membrane, and other suitable types of reflective structures.

In these illustrative examples, first reflective structure **200** and second reflective structure **202** may allow some or all light in an optical signal to pass through the reflective structures. For example, these reflective structures may allow light of some frequencies to pass through the reflective structures. The amount of light and the frequency of light that may be passed or reflected by the reflective structures may depend on various parameters. For example, pressure, temperature, and other parameters may affect the amount of light and frequency of the light reflected by the reflective structures.

In this illustrative example, the different components are configured to generate information within response **130**. For example, first reflective structure **200** is configured to generate information about temperature **120**. Cavity system **204** with first reflective structure **200** and second reflective structure **202** are configured to generate information about pressure **122**. Second reflective structure **202** is configured to generate information about refractive index **124**.

The information in response **130** may be, for example, a frequency of light, an intensity of light, and other characteristics about the light reflected in optical signal **128**. Other examples include at least one of frequency shift, phase of light, spectral shape, quality factor (Q) of spectral peaks or valleys, and dispersion of a pulse.

The illustration of sensor environment **100** and the different components in sensor environment **100** in FIG. **1** and FIG. **2** is not meant to imply physical or architectural limitations to the manner in which an illustrative embodiment may be implemented. Other components in addition to or in place of the ones illustrated may be used. Some components may be unnecessary. Also, the blocks are presented to illustrate some functional components. One or more of these blocks may be combined, divided, or combined and divided into different blocks when implemented in an illustrative embodiment.

For example, other types of sensors may be present in sensor system **104** in addition to optical sensor units **114**. For example, wired sensor units also may be present in these illustrative examples. In still other illustrative examples, the group of optical sensor units **114** may not be directly connected to measurement system **110** by optical fibers **112**. Instead, optical fibers **112** may be connected to wireless indications units that transmit response **130**. Response **130** may be transmitted as an optical signal over air, rather than through an optical fiber. In other illustrative examples, response **130** may be converted into digital or analog form in a signal that is transmitted over a wireless indications link.

In yet another illustrative example, optical sensor unit **118** may have one or more sealed cavities within group of cavities **208** in addition to sealed cavity **210**. First reflective structure **200** and second reflective structure **202** may be located on either side of these additional sealed cavities. In yet other illustrative examples, additional reflective structures may be present in addition to first reflective structure **200** and second reflective structure **202**.

In FIG. **3**, an illustration of an optical sensor unit associated with optical fiber is depicted in accordance with an illustrative embodiment. In this illustrative example, optical sensor unit **300** is shown associated with optical fiber **302**. Optical sensor unit **300** is an example of one physical implementation for optical sensor unit **118** shown in block form in FIG. **1** and FIG. **2**.

In one illustrative example, optical sensor unit **300** associated with optical fiber **302** may be placed in an area of a platform such as a fuel tank or an engine of an aircraft. For example, when optical sensor unit **300** is used in a fuel tank, optical sensor unit **300** may detect temperature, pressure, and refractive index for the fuel tank. The refractive index may be used to identify the composition of the fuel in the fuel tank. For example, the refractive index may be used to determine whether contaminants are present, whether the fuel has a desired level of quality, or some combination thereof. A more detailed view of section **304** is shown and described with reference to FIG. **4** below.

Turning now to FIG. **4**, a more detailed illustration of a sensor unit associated with an optical fiber is depicted in accordance with an illustrative embodiment. In particular, a more detailed view of section **304** from FIG. **3** is shown.

As can be seen in this view, optical sensor unit **300** is formed from substrate **400**. In this particular example, substrate **400** is a silicon substrate. Of course, other types of substrates may be used depending on the particular implementation. For example, a silicon on insulator (SOI) substrate also may be used as well as other suitable substrates. Substrate **400** forms housing structure **402** for optical sensor unit **300**.

In this illustrative example, housing structure **402** has a shape of a cuboid. Cross-section of housing structure **402** has a rectangular shape. Of course, housing structure **402** may have other shapes in other illustrative examples. For example, housing structure **402** may have the shape of a cube, a cylinder, or some other suitable shape depending on the particular implementation.

Different components for optical sensor unit **300** are shown in phantom inside of housing structure **402**. Within housing structure **402**, first photonic crystal mirror **404**, sealed cavity **406**, and second photonic crystal mirror **408** can be seen in phantom.

As depicted, first photonic crystal mirror **404** is located in section **410**, sealed cavity **406** is located in section **412**, and second photonic crystal mirror **408** is located in section **414**. These different components provide optical sensor unit **300** with the capability to detect at least one of temperature, pressure, and refractive index.

In this illustrative example, channels **416** are seen in housing structure **402**. Although channels **416** are shown with a rectangular grid, other configurations of channels **416** may be present. For example, channels **416** may be arranged as a hexagonal grid.

In FIG. **5**, an illustration of a cross-sectional view of an optical sensor unit associated with an optical fiber is depicted in accordance with an illustrative embodiment. A cross-sectional view of optical sensor unit **300** associated with optical fiber **302** in section **304** is seen taken along line **5-5** in FIG. **4**.

As depicted, optical sensor unit **300** is associated with core **500** inside of cladding **501** of optical fiber **302**. The association is such that optical signal **502** may be transmitted into optical sensor unit **300** and response **503** may be received from optical sensor unit **300**.

In this illustrative example, the different components within optical sensor unit **300** function together to provide information about a number of different parameters. In particular, first photonic crystal mirror **404**, sealed cavity **406**, and second photonic crystal mirror **408** are configured such that changes in these components are reflected in response **503**. As a result, response **503** provides information about a combination of parameters such as temperature, pressure, and refractive index.

In some illustrative examples, one or more parts of optical sensor unit **300** may be more sensitive to one or more different parameters than other parts of optical sensor unit **300**. As an example, first photonic mirror **404** is more sensitive to changes in temperature because first photonic crystal mirror **404** is encapsulated within optical sensor unit **300**. In other words, because of the position of first photonic crystal mirror **404** within optical sensor unit **300**, changes to pressure and refractive index outside optical sensor unit **300** may have a negligible effect on first photonic crystal mirror **404**.

As another example, sealed cavity **406** is more sensitive to changes in pressure. Sealed cavity **406** may expand and contract as the pressure around the object changes. As yet another example, second photonic crystal mirror **408** is more sensitive to changes in refractive index. Thus, depending on the type of changes occurring with respect to the object, the combination of reflectivities of first photonic crystal mirror **404**, sealed cavity **406**, and second photonic crystal mirror **408** provide information in response **503** about at least one of temperature, pressure, and refractive index.

In operation, optical signal **502**, having a first frequency, may be sent into optical sensor unit **300**. Optical signal **502** may be reflected as response **503**. The intensity of the light in optical signal **502** that is reflected as response **503** by optical sensor unit **300** may vary depending on the temperature. Additionally, the frequency may also change depending on the temperature. In these illustrative examples, the frequency is the frequency of the spectral content of the light in response **503**.

Optical signal **502** may be sent into optical sensor unit **300** having a second frequency that is different from the first frequency. Sealed cavity **406**, first photonic crystal mirror **404**, and second photonic crystal mirror **408** may generate response **503** that includes information about pressure.

For example, as the pressure on housing structure **402** changes, the size of sealed cavity **406** also may change. The change in the manner in which optical signal **502** is reflected within sealed cavity **406** between first photonic crystal mirror **404** and second photonic crystal mirror **408** may be used to identify the pressure on housing structure **402**. In particular, this change may be the intensity of the light in response **503**. This change may be used identify the distance between first photonic crystal mirror **404** and second photonic crystal mirror **408**. This distance may change as pressure changes. As a result, the distance may be used to identify the pressure.

A third frequency may be selected for optical signal **502** to detect a refractive index of the environment around optical sensor unit **300**. The environment around optical sensor unit **300** may be, for example, a fluid. This fluid may be, for example, fuel. In this instance, response **503** from the components in optical sensor unit **300** may contain information needed to identify the refractive index of the fluid.

With reference now to FIG. **6**, an illustration of optical sensor units in a silicon substrate is depicted in accordance with an illustrative embodiment. In this illustrative example, optical sensor units **600** are shown in silicon substrate **602**. As depicted, silicon substrate **602** takes the form of a silicon wafer.

Optical sensor units **600** may be formed in silicon substrate **602** using currently available semiconductor processing techniques. Optical sensor units **600** may then be separated from silicon substrate **602** and attached to optical fibers.

Optical sensor unit **604** is an example of an optical sensor unit within optical sensor units **600**. A more detailed illustration of optical sensor unit **604** is shown in FIG. **7** below.

In FIG. **7**, an illustration of a cross-sectional view of an optical sensor unit in a wafer is depicted in accordance with an illustrative embodiment. In this illustration, a cross-sectional view of optical sensor unit **604** is shown taken along line **7-7** in FIG. **6**.

In this cross-sectional view, optical sensor unit **604** has first photonic crystal mirror **700**, second photonic crystal mirror **702**, and sealed cavity **704**. Also seen in this cross-sectional view is release cavity **706** and portion **708**.

In the illustrative example, release cavity **706** and portion **708** in silicon substrate **602** are not part of optical sensor unit **604**. Instead, these components are used to fabricate optical sensor unit **604** using semiconductor processes. Portion **708** is discarded or removed when separating optical sensor unit **604** from silicon substrate **602**. As a result, surface **710** forms an outer surface for optical sensor unit **604** when optical sensor unit **604** is removed from silicon substrate **602**.

With reference to FIGS. **8-14**, illustrations of cross-sectional views for a process for fabricating an optical sensor unit on a silicon substrate is depicted in accordance with an illustrative embodiment. In this illustrative example, the forming of the optical sensor unit is performed using reactive ion etching (RIE).

In FIG. **8**, a cross-sectional view of a substrate with a thermal oxide layer is depicted in accordance with an illustrative embodiment. In this depicted example, silicon substrate **800** is shown with thermal oxide layer **802** formed on surface **804** of silicon substrate **800**. In this illustrative example, thermal oxide layer **802** is about 700 nm thick. Silicon substrate **800** may be a standard silicon wafer which is about 400 um to about 500 um thick. In other illustrative examples, silicon substrate **800** may be a silicon wafer from about 200 um to about 1 mm thick. For example, if silicon substrate **800** is a 4 in silicon wafer, the thickness may be from about 300 um to about 600 um.

Next, in FIG. **9**, a cross-sectional view of a substrate with patterned photoresist is depicted in accordance with an illustrative embodiment. In this illustrative example, photoresist layer **900** has been formed on thermal oxide layer **802**. As depicted, photoresist layer **900** is about 700 nm thick.

In addition, photoresist layer **900** is shown in a patterned form. The pattern in photoresist layer **900** includes openings **902**. Openings **902** expose portions of thermal oxide layer **802** for etching. In this illustrative example, thermal oxide layer **802** is already etched and exposes portions of surface **804** of silicon substrate **800**. In this illustrative example, an opening in openings **902** may be spaced apart from another opening by distance of about 820 nm from center to center.

Portions of thermal oxide layer **802** are removed where openings **902** are present. In this illustrative example, reactive ion etching (RIE) is used to remove this portion of thermal oxide layer **802**. The removal of the portions of thermal oxide layer **802** exposes portions of surface **804** of silicon substrate **800**. Photoresist layer **900** is removed after portions of surface **804** of silicon substrate **800** have been exposed.

In FIG. **10**, reactive ion etching (RIE) has been performed on the exposed portions of surface **804** of silicon substrate **800**. The result is channels **1000** that extend into silicon substrate **800**. Thermal oxidation is performed to form thermal oxide layer **1002** on the walls of channels **1000**. In the illustrative example, the thickness of the thermal oxide on the walls of channels **1000** is about 70 nm.

Further, only four channels are shown in this cross-sectional view of channels **1000** for the purpose of more clearly illustrating how different structures are manufactured. Additional channels are not shown to avoid obscuring the illustration of how different structures are fabricated for an optical sensor unit. In fact, in an actual optical sensor unit, thousands of channels may be present. For example, channels **1000** may be arranged in a grid of 200×200 channels. Thus, the cross-section in this example has 200 channels.

As depicted, portions of thermal oxide layer **1002** have been removed from bottom side **1004** of channels **1000**. The removal of these portions exposes silicon substrate **800** on bottom side **1004** of channels **1000**. In the illustrative example, channels **1000** may have a diameter of about 500 nm. The diameter of channels **1000** may be selected such that channels **1000** may be sealed using thermal oxidation.

In FIG. **11**, a reactive ion etch is performed to extend channels **1000** further into silicon substrate **800**. Extended portions (not shown) do not have thermal oxide layer **1002**.

Thereafter, an isotropic undercut etch is performed using SF_6 in this illustrative example. Of course, the isotropic undercut etch may be performed using other chemicals, depending on the particular implementation. For example, CF_4 may also be used. These steps result in the formation of cavity **1100**, cavity **1102**, and cavity **1104**. Layer **1106** is located above cavity **1102**. Layer **1106** has a thickness of about 500 nm. Layer **1106** is the section that will form the first mirror. When fabrication is complete, the membrane is suspended on silicon substrate **800**. Layer **1106**, the area above cavity **1102**, is a photonic crystal membrane in this illustrative example. Layer **1106** is attached to silicon substrate **800** by the two sides. The sides are pillar structure **1103** and pillar structure **1105**. Pillar structure **1103** is located between cavity **1100** and cavity **1102**. Pillar structure **1105** is located between cavity **1102** and cavity **1104**. Even though the cross-section shows two pillars, it's actually a ring in the 3D structure. The ring can be any enclosed polygon, though it's most commonly a circle or a square.

Next, in FIG. **12**, channels **1200** have been etched into silicon substrate **800** and thermal oxide layer **1202** has been formed on the walls of channels **1200**. Additionally, thermal oxide layer **1202** has also been formed in cavity **1100**, cavity **1102**, and cavity **1104**. In this illustrative example, each of channels **1200** has a diameter of about 400 nm or less. In a similar fashion, portions of thermal oxide layer **1202** have been removed from bottom side **1204** of the walls of channels **1200**.

Turning to FIG. **13**, an isotropic undercut etch is performed in accordance with an illustrative embodiment. In particular, reactive ion etching is performed to extend channels **1200**. The extension of channels **1200** do not have thermal oxide layer **1202**.

Thereafter, the isotropic undercut etch may be performed using XeF_2 and results in the formation of cavity **1300**. Of course, other chemicals may be used to perform the isotropic undercut edge. For example, CF_4 and SF_6 also may be used. In this illustrative example, layer **1302** is located between cavity **1102** and cavity **1300**. Layer **1302** has a thickness of about 400 nm and is the section that will form the section for the second photonic crystal mirror when processing is complete in this illustrative example.

Next, in FIG. **14**, thermal oxide layer **1400** is formed in cavity **1300**. The formation of thermal oxide also seals channels **1000** and the portion of channels **1200** that are connected to cavity **1102**. Thus, the formation of thermal oxide is such that cavity **1102** becomes sealed cavity **1402** in this illustrative example. As depicted, cavity **1300** is in communication with cavity **1100** and cavity **1104**. Cavity **1100** is in communication with channel **1404** in layer **1106** and cavity **1104** is in communication with channel **1406** in layer **1106**. This configuration aids in sealing cavity **1102** to form sealed cavity **1402**.

As can be seen, layer **1106** includes thermal oxide layer **802**, silicon substrate **800** within layer **1106**, channels **1000** filled with thermal oxide, and thermal oxide layer **1408** formed on topside **1410** of sealed cavity **1402**. Layer **1302** includes thermal oxide layer **1412** on bottom side **1414** of sealed cavity **1402**, channels **1200** filled with thermal oxide, and silicon substrate **800**.

These layers, however, do not include portion **1416**. Portion **1416** is a removable portion and may be removed to form optical sensor unit **1418**.

The illustrations of the different cross-sections and descriptions of the steps for forming an optical sensor unit are not meant to show every step in fabricating an optical sensor unit on a silicon substrate. The different cross-sections shown are meant to illustrate some of the steps used to manufacture the optical sensor unit. For example, a cross-sectional view of unpatterned photoresist was not shown. Further, the different structures shown in the cross-sectional views are not meant to be proportional or show actual dimensions of the optical sensor unit.

As another illustrative example, the different steps depicted may also be used with other substrates other than a silicon substrate. For example, silicon on insulator (SOI) substrate may be used.

With reference next to FIG. **15**, an illustration of a cross-sectional view of an optical sensor unit is depicted in accordance with an illustrative embodiment. Optical sensor unit **1500** is an example of one physical implementation for optical sensor unit **118** in FIG. **1**. In this illustrative example, optical sensor unit **1500** has first reflective structure **1502** in section **1504**, sealed cavity **1506** in section **1508**, and second reflective structure **1510** in section **1512**.

As seen in this example, first reflective structure **1502** includes channels **1514**, cavities **1516**, and channels **1518**. These three layers may provide increased reflectivity. Additionally, the configuration of these three layers may increase the sensitivity of optical sensor unit **1500** with respect to detecting temperature and pressure.

With reference next to FIG. **16**, another illustration of a cross-sectional view of an optical sensor unit is depicted in accordance with an illustrative embodiment. Optical sensor unit **1600** is an example of one physical implementation for optical sensor unit **118** in FIG. **1**. In this illustrative example, optical sensor unit **1600** has first reflective structure **1602** in section **1604**, sealed cavity **1606** in section **1608**, and second reflective structure **1610** in section **1612**.

As seen in this illustrative example, first reflective structure **1602** has channels **1614**, cavities **1616**, and channels **1618** that are arranged in three layers. Additionally, second reflective structure **1610** has channels **1620** and cavities **1622** arranged in two layers. These two layers may provide increased sensitivity in detecting a parameter. For example, these two layers may provide increased sensitivity in detecting pressure.

With reference to FIG. **17**, yet another illustration of a cross-sectional view of an optical sensor unit is depicted in accordance with an illustrative embodiment. Optical sensor unit **1700** is an example of one physical implementation for optical sensor unit **118** in FIG. **1**. In this illustrative example, optical sensor unit **1700** has first reflective structure **1702** in section **1704**, sealed cavities **1706** in section **1708**, and second reflective structure **1710** in section **1712**.

First reflective structure **1702** includes channels **1714**, cavities **1716**, and channels **1718**. These structures are arranged in three layers in this illustrative example. Second reflective structure **1710** includes channels **1720** and cavities **1722** arranged in two layers.

In this illustrative example, cavities **1706** are present in place of a single cavity as shown in other examples. Cavities **1706** may provide a more robust structure for optical sensor unit **1700**. In other words, cavities **1706** may result in an increase in strength of the structure that forms the sensor unit. With increased strength, changes in pressure become less sensitive. As a result, other parameters such as temperature and refractive index may be more easily identified.

The different components shown in FIGS. **3-17** may be combined with components in FIGS. **1-2**, used with components in FIGS. **1-2**, or a combination of the two. Additionally, some of the components in FIGS. **3-17** may be illustrative examples of how components shown in block form in FIGS. **1-2** can be implemented as physical structures.

With reference now to FIG. **18**, an illustration of a flowchart of a process for detecting a number of parameters is depicted in accordance with an illustrative embodiment. The process illustrated in FIG. **18** may be implemented using sensor system **104** with optical sensor units **114** in FIG. **1**.

The process begins by sending an optical signal into an optical sensor unit (operation **1800**). The process then receives a response generated by the optical sensor unit (operation **1802**). Thereafter, a number of parameters are identified from the response (operation **1804**) with the process terminating thereafter.

Turning next to FIG. **19**, an illustration of a flowchart of a process for forming an optical sensor unit is depicted in accordance with an illustrative embodiment. The different operations illustrated in this flowchart may be used to form optical sensor unit **118** in FIG. **1**.

The process begins by forming first channels in a silicon substrate with thermal oxide on the walls of the channels (operation **1900**). The channels may be formed using reactive ion etching in this illustrative example. The layer in which these channels are located is part of the first reflective structure.

The process then forms a cavity below the layer containing the first channels (operation **1902**).

The process then forms second channels, with thermal oxide on the walls of the second channels (operation **1904**). This operation also forms thermal oxide in the cavity. This thermal oxide on the upper portion of the cavity is part of the first reflective structure. The thermal oxide on the lower portion of the cavity is part of the second reflective structure.

The channels are aligned with the channels in the upper layer above the cavity. The layer in which these second channels are located is part of the second reflective structure.

The process then forms additional thermal oxide that seals the first channels and the second channels such that the cavity becomes a sealed cavity (operation **1906**) with the process terminating thereafter.

The flowcharts and block diagrams in the different depicted embodiments illustrate the architecture, functionality, and operation of some possible implementations of apparatuses and methods in an illustrative embodiment. In this regard, each block in the flowcharts or block diagrams may represent a module, a segment, a function, and/or a portion of an operation or step.

In some alternative implementations of an illustrative embodiment, the function or functions noted in the blocks may occur out of the order noted in the figures. For example, in some cases, two blocks shown in succession may be executed substantially concurrently, or the blocks may sometimes be performed in the reverse order, depending upon the functionality involved. Also, other blocks may be added in addition to the illustrated blocks in a flowchart or block diagram.

For example, additional operations may be performed in forming the optical sensor unit in the flowchart in FIG. **19**. These additional operations may include forming additional cavities in the first reflective structure and the second reflective structure.

Illustrative embodiments may be described in the context of aircraft manufacturing and service method **2000** as shown in FIG. **20** and aircraft **2100** as shown in FIG. **21**. Turning first to FIG. **20**, an illustration of an aircraft manufacturing and service method is depicted in accordance with an illustrative embodiment. During pre-production, aircraft manufacturing and service method **2000** may include specification and design **2002** of aircraft **2100** in FIG. **21** and material procurement **2004**.

During production, component and subassembly manufacturing **2006** and system integration **2008** of aircraft **2100** in FIG. **21** take place. Thereafter, aircraft **2100** in FIG. **21** may go through certification and delivery **2010** in order to be placed in service **2012**. While in service **2012** by a customer, aircraft **2100** in FIG. **21** is scheduled for routine maintenance and service **2014**, which may include modification, reconfiguration, refurbishment, and other maintenance or service.

Each of the processes of aircraft manufacturing and service method **2000** may be performed or carried out by a system integrator, a third party, and/or an operator. In these examples, the operator may be a customer. For the purposes of this description, a system integrator may include, without limitation, any number of aircraft manufacturers and major-system subcontractors; a third party may include, without limitation, any number of vendors, subcontractors, and suppliers; and an operator may be an airline, a leasing company, a military entity, a service organization, and so on.

With reference now to FIG. **21**, an illustration of an aircraft is depicted in which an illustrative embodiment may be implemented. In this example, aircraft **2100** is produced by aircraft manufacturing and service method **2000** in FIG. **20** and may include airframe **2102** with plurality of systems **2104** and interior **2106**. Examples of systems **2104** include one or more of propulsion system **2108**, electrical system **2110**, hydraulic system **2112**, environmental system **2114**, and sensor system **2116**. Any number of other systems may be included. Although an aerospace example is shown, different illustrative embodiments may be applied to other industries, such as the automotive industry.

Apparatuses and methods embodied herein may be employed during at least one of the stages of aircraft manufacturing and service method **2000** in FIG. **20**.

In one illustrative example, components or subassemblies produced in component and subassembly manufacturing **2006** in FIG. **20** may be fabricated or manufactured in a manner similar to components or subassemblies produced while aircraft **2100** is in service **2012** in FIG. **20**. As yet another example, one or more apparatus embodiments, method embodiments, or a combination thereof may be utilized during production stages, such as component and subassembly manufacturing **2006** and system integration **2008** in FIG. **20**. For example, optical sensor units may be manufactured and installed in sensor system **2116** during component and subassembly manufacturing **2006** and system integration **2008**.

One or more apparatus embodiments, method embodiments, or a combination thereof may be utilized while aircraft **2100** is in service **2012** and/or during maintenance and service **2014** in FIG. **20**. For example, optical sensor units may be used to detect various parameters in different areas of aircraft **2100**, such as fuel tanks, engines, auxiliary power units, a passenger cabin, or other suitable areas of aircraft **2100**. As another example, optical sensor units may be installed during upgrade, refurbishment, brother maintenance in maintenance and service **2014**. The use of a number of the different illustrative embodiments may substantially expedite the assembly of and/or reduce the cost of aircraft **2100**.

Thus, with optical sensor units such as those illustrated in the different figures, a reduction in the size and weight of sensor systems in aircraft may be achieved as compared to using electrical sensors. Further, the optical sensor units do not need shielding her grounding and are not affected by electromagnetic interference.

The illustrative embodiments may be especially useful in different areas of an aircraft such as a fuel tank, engine, or some other suitable area. Further, with the use of optical sensors, the amount of power needed to operate a sense system also may be reduced.

Further, with an optical sensor unit being able to detect multiple parameters, holes formed in a fuel tank to provide information about the parameters may be reduced. Further, with shielding and other isolation being unnecessary as compared to electrical sensors, the complexity in the design and installation of sensor systems may be reduced for an aircraft.

The description of the different illustrative embodiments has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the embodiments in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art.

Further, different illustrative embodiments may provide different features as compared to other illustrative embodiments. The embodiment or embodiments selected are chosen and described in order to best explain the principles of the embodiments, the practical application, and to enable others of ordinary skill in the art to understand the disclosure for various embodiments with various modifications as are suited to the particular use contemplated.

What is claimed is:

1. An apparatus comprising:

an optical sensor unit comprising:

a first reflective structure configured to be associated with an optical fiber;

a second reflective structure; and

a cavity system located between the first reflective structure and the second reflective structure;

wherein the cavity system is a sealed cavity system;

wherein the first reflective structure and the cavity system include a second cavity and a first channel between the first reflective structure and the cavity system; and

wherein the second reflective structure and the cavity system include a third cavity and a second channel between the second reflective structure and the cavity system.

2. The apparatus of claim **1**, wherein the optical sensor unit is configured to generate a response to an optical signal including information about a temperature, a pressure, and a refractive index.

3. The apparatus of claim **1**, wherein the cavity system is comprised of a group of cavities.

4. The apparatus of claim **1**, wherein the first reflective structure, the second reflective structure, and the cavity system are formed on a substrate selected from one of a silicon substrate and a silicon on insulator substrate.

5. The apparatus of claim **1**, wherein the optical fiber is selected from one of a multimode optical fiber and a single mode optical fiber.

6. The apparatus of claim **1**, further comprising:

a measurement system configured to send an optical signal into the optical sensor unit through the optical fiber and detect a response to the optical signal generated by the optical sensor unit.

7. The apparatus of claim **1**, wherein the first reflective structure is configured to generate information about a temperature.

8. The apparatus of claim **1**, wherein the second reflective structure is configured to generate information about a pressure.

9. The apparatus of claim **1**, wherein the first reflective structure, the second reflective structure, and the cavity system are configured to generate information about a refractive index.

10. The apparatus of claim **1**, wherein the first reflective structure and the second reflective structure are each selected from one of a photonic crystal mirror, a layer of metal, a layer of dielectric, a grating, a Bragg grating, and a membrane.

11. An optical sensor unit comprising:

a first photonic crystal mirror;

a second photonic crystal mirror; and

a sealed cavity located between the first photonic crystal mirror and the second photonic crystal mirror;

wherein the first photonic crystal mirror and the sealed cavity include a second cavity and a first channel between the first photonic crystal mirror; and

wherein the second photonic crystal mirror and the sealed cavity include a third cavity and a second channel between the second photonic crystal mirror and the sealed cavity.

12. The optical sensor unit of claim 11 further comprising: an optical fiber associated with the first photonic crystal mirror.

13. The optical sensor unit of claim 11, wherein the first photonic crystal mirror is configured to generate information about a temperature.

14. The optical sensor unit of claim 11, wherein the second photonic crystal mirror is configured to generate information about a pressure.

15. The optical sensor unit of claim 11, wherein the first photonic crystal mirror, the second photonic crystal mirror, and the sealed cavity are configured to generate information about a refractive index.

16. A method for detecting a group of parameters, the method comprising:

sending an optical signal into an optical sensor unit comprising a first reflective structure configured to be associated with an optical fiber, a second reflective structure, and a cavity system located between the first reflective structure and the second reflective structure;

detecting a response generated by the optical sensor unit; and

identifying the group of parameters from the response;

wherein the first reflective structure and the cavity system include a second cavity and a first channel between the first reflective structure and the cavity system; and

wherein the second reflective structure and the cavity system include a third cavity and a second channel between the second reflective structure and the cavity system.

17. The method of claim 16, wherein the group of parameters is selected from a temperature, a pressure, and a refractive index.

18. The method of claim 16, wherein the optical sensor unit is located in an aircraft.

19. The apparatus of claim 1, wherein the first reflective structure is sensitive to a change in temperature and the second reflective structure is sensitive to a change in pressure.

20. The apparatus of claim 1, wherein the cavity system comprises a single cavity.

* * * * *